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Scalability of Robotic Controllers: Effects of Progressive Autonomy on Intelligence, Surveillance, and Reconnaissance Robotic Tasks

by Rodger A. Pettitt, Elizabeth S. Redden
Christian B. Carstens, and David Hooper

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14. ABSTRACT Multiple task demands of robotic operators can result in cognitive overload. We investigated the utility of offloading some of the operator tasks by examining three levels of automation: (1) teleoperation, (2) semi-autonomy (teleoperation with obstacle avoidance) and, (3) autonomy (reflexive waypoint navigation with obstacle avoidance) for intelligence, surveillance, and reconnaissance of an area. Using a within-subjects design, twenty-seven Soldiers navigated a robot along a route littered with obstacles while looking for unexploded ordinance using the three levels of automation. They completed each condition twice, once while concurrently engaged in secondary cognitive tasks, and once without the secondary tasks. The secondary tasks interfered with course navigation in the teleoperation and semi-autonomous control conditions, but not in the autonomous control condition. Mental workload ratings were also higher in the teleoperation and semi-autonomous conditions than in the autonomous condition. There were more driving errors in the teleoperation condition than in the semi-autonomous and autonomous conditions. Although the automatic obstacle avoidance feature of the semi-autonomous condition reduced errors, it adversely impacted course completion times and made the operators feel as though they were competing with the feature for control of the robot. The Soldiers preferred full autonomy for all the navigation/maneuver tasks.						
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1. Introduction

1.1 Background

Because Infantry Soldiers operating ground robots typically have multiple task demands, reducing the tasks involved in robotic control should help mitigate potential cognitive overload. Maes' (1995) continuum of robot control that ranges from teleoperation to full autonomy allows robots to be placed on a continuum based on the level of human-robot interaction that is required. Teleoperation is the lowest level of automation on the continuum because it requires the most intervention from the robot operator. A teleoperated robot is totally under the control of the operator who uses a joystick or other control device to command the robot. This requires constant interaction between the robot and the operator. Teleoperation is not the ideal solution for all situations. Many teleoperation tasks are repetitive and boring and the work requires constant attention by the operator.

Semi-autonomous control (often called supervisory control) requires the operator to provide an instruction or portion of a task that can safely be performed by the robot on its own. Two types of semi-autonomous control are often identified—shared control (also called continuous assistance) and control trading. Shared control requires the teleoperator to delegate a task for the robot or to accomplish it via direct control of the robot. If the operator delegates control to the robot, then he or she must still monitor the robot to ensure that it is performing the task correctly. A guarded teleoperated robot can be placed on this portion of the continuum because it has the ability to sense and avoid obstacles but will otherwise navigate as driven, like a robot under manual teleoperation. During control trading, the human only interacts with the robot to give it a new command or to dynamically re-task its mission. A line-following robot can be placed on this portion of the continuum if it simply follows something painted, embedded or placed on the floor and does not have the ability to circumnavigate obstacles on its own.

After receiving instructions, autonomous robots (those that perform tasks independently and/or have the capacity to choose goals for themselves) operate under all reasonable conditions without recourse to an outside operator and can handle unpredictable events (Haselager, 2005). Huang et. al (2005) state that a fully autonomous robot has the ability to gain information about the environment, work for an extended period without human intervention, move itself through its environment without human assistance, and avoid situations that are harmful to people, property, or itself unless those are part of its design specifications. An autonomously guided robot can be placed on this portion of the continuum because it knows at least some information about where it is and how to reach waypoints (Murphy, 2000). Knowledge of its current location is determined by using sensors such as lasers and global positioning systems (GPS). Positioning systems determine the location and orientation of the platform, so the robots can plan a path to their next waypoints or goals. Autonomous robots make their own choices instead of following

goals set by other agents. A robot that is capable of goal generation can also be placed on this portion of the continuum.

The incorporation of autonomous robotic systems into military schema involves more than just effective system design. It is also important for designers to understand which robotic system autonomous capabilities match or surpass human abilities and when, during scenario accomplishment, the human needs assistance or is overloaded. This knowledge is needed in order to leverage autonomous robotic behaviors for optimal performance. Thus, the goal is to optimize the human and robot roles in a task. To do this, robot control competencies and inefficiencies must first be identified and then they must be understood in relation to specific task performance. Trade-offs among levels of autonomy and moderators of robot control performance must be identified. For example, workload is an important moderator of human task performance. The effectiveness of a control system is likely to depend a great deal on situational task demands. The requirement for the operator to perform simultaneous tasks such as controlling multiple robots or performing local security tasks could have a detrimental effect on human intervention in robotic task outcomes because of human availability at a certain point in time and because of cognitive overload.

Many studies have demonstrated that operators' situation awareness (SA) was higher when they were controlling robots with semi-autonomous or autonomous capabilities (Chen et. al, 2008; Dixon et. al, 2003; Luck et al., 2006). However, increased autonomy is not always the most effective choice. Chen and Joyner (2006) found that participants detected fewer targets when their robot was operating in the semi-autonomous mode rather than the teleoperation mode. In a two-year study of a collaborative human-robot system, Stubbs et. al (2007) found that as autonomy increased, users' inability to understand the reasons for the robot's actions disrupted the creation of common ground. Also, many fear that providing more and more autonomy to armed robots could result in collateral damage or fratricide (Singer, 2009).

In a recent reconnaissance experiment on progressive autonomy in robots (Pettitt et al., 2010), the participants agreed that mapping a room, driving the robot, and responding to queries from the white cell in the teleoperation mode created task demands that were too difficult. The Soldiers rated teleoperation as creating a higher cognitive and overall workload and higher stress (frustration) than semi- and fully autonomous operation. While Dixon and Wickens (2003) suggested that automation would relieve cognitive overload, offloading some of the tasks by use of the autonomous and semi-autonomous modes relieved more than just the cognitive load and made the performance of the tasks much more manageable. It was clear that the operators' mental models of the environment, based upon viewing it through a robotic driving camera, were fairly inaccurate because map accuracy in the teleoperation mode was much poorer than in the autonomous and semi-autonomous modes. This supports the findings of Fong et. al (2003) who indicated that operators using teleoperation have difficulty building mental models of remote environments.

In this study, we again examine three levels of automation: (1) teleoperation, (2) semi-autonomy (teleoperation with obstacle avoidance) and, (3) autonomy (reflexive waypoint navigation with obstacle avoidance) for a new task, intelligence, surveillance, and reconnaissance (ISR) of an area. Once again, our hypothesis is that full autonomy will be the most effective level of autonomy for this mission when the robotic operator is fully engaged in a high cognitive load activity.

1.2 Objective

The goal of this research was to examine the effectiveness of different levels of automation on robot control in ISR missions when the robotic operator is fully engaged in a high cognitive load activity.

1.3 Overview Experiment

This study was a cooperative research effort between the U.S. Army Research Laboratory (ARL)-Human Research and Engineering Directorate (HRED) and Space and Naval Warfare Systems Center, San Diego, (SSC Pacific). The study was an investigation of the effects of progressive levels of autonomy on ISR robotic navigation tasks. It took place at Fort Benning, GA, and 27 Soldiers from the Officer Candidate School (OCS) participated in the study. After training on the operation of the robotic system, each participant navigated the robot along a route littered with obstacles while looking for unexploded ordinance (UXO) using three different levels of robotic automation (teleoperated, semi-autonomous, and autonomous). During the exercise, Soldiers responded to requests for information regarding situation and mission awareness. The hazards and the automation level were counterbalanced to control for the effect of learning. Automation level and usability were evaluated based on objective performance data, data collector observations, and Soldier questionnaires.

2. Method

2.1 Participants

Twenty-seven Soldiers from the Fort Benning OCS participated in the assessment. The OCS participants included Soldiers with prior enlisted service with a variety of backgrounds and experience levels, as well as those just coming into the Army from college.

2.1.1 Pretest Orientation

The Soldiers were given an orientation on the purpose of the study and what their participation would involve. They were briefed on the objectives, procedures, and the robotic system. They were also told how the results would be used and the benefits the military could expect from this investigation. Any questions the subjects had regarding the study were answered.

2.2 Apparatus and Instruments

2.2.1 SSC Pacific Robot

The SSC Pacific robot (figure 1) is a high mobility long-range surveillance robot with long range communication, extended mission endurance, and an ISR sensor suite appropriate for long range ground surveillance. Autonomous Solutions Incorporated Chaos platform hosts the sensor suite. The payload contains forward-looking infrared radar's (FLIR's) D100E Pan/Tilt Unit, a Small Tactical Optical Rifle Mounted (STORM) Micro-laser Rangefinder, a camera suite consisting of a thermal 100-mm fixed lens, a color Day/Night Electron Multiplying Charge Coupled Device (EMCCD) Camera 300-mm zoom lens, and a color Day/Night EMCCD Camera 8-mm fixed lens. A GPS is used for navigation. In addition, the payload contains a processor that runs all the autonomous behaviors onboard the robot and a radio to communicate with the operator control unit.

Figure 1. SSC Pacific robot.

2.2.2 Operator Interface

The operator interface used to control the system is SSC Pacific's Multi-Robot Operator Control Unit (MOCU). The robot's location, driven path, and goal points are overlaid on an aerial image. Real-time video from the robot is also displayed. The controller is a Microsoft Xbox* 360 Game Controller and a touch screen upon which the control functions have been mapped. Various button controls are provided to send drive commands to the robot, as well as to change the robot's behaviors.

* Microsoft and Microsoft Xbox are registered trademarks of Microsoft Corporation in the United States and other countries.

The interface allows the operator to achieve a type of sliding autonomy with the robot. Levels of autonomy are achieved by turning on and off robot behaviors. All behaviors were turned off during teleoperation so that the operator was in complete control of all robot actions. Semi-autonomy (reflexive teleoperation) was achieved by using the guarded teleoperation function available on the robot. This function assists the robot operator during driving by automatically avoiding obstacles. With reflexive teleoperation, the operator controlled the robot's movement through the joystick. The robot was able to override the user's commands to avoid obstacles when necessary. Full autonomy was achieved by turning on the guarded teleoperation behavior and autonomous waypoint navigation. In this level of autonomy, the operator set the robot's desired destination and intermediary points and the robot traversed from point to point utilizing GPS data. The robot can deviate from these paths when necessary for obstacle avoidance. Due to intermittent GPS satellite coverage experienced at the test site, a representative from SSC Pacific simulated full autonomy by manually controlling the robot during the fully autonomous trials.

The MOCU software was developed independent of the hardware unit, and thus can be used on any computer with a Windows XP[†] or newer operating system. A commercial off-the-shelf (COTS) grade laptop was used in the experiment to run MOCU. A Microsoft Xbox 360 controller was used to provide a joystick interface for manual driving of the robot.

2.2.3 Robotic Reconnaissance Route

The reconnaissance route (figure 2) was on a 200-m length of roadway littered with obstacles. The obstacles were arranged in a manner that allowed the operator to maneuver the robot around them without having to leave the roadway. Fifteen UXOs were placed along the route at various points. The start point and end point were marked with engineer tape. A different configuration of obstacle and UXO placement was used for each iteration. The operator was located at a stationary control station outside the line of sight of the route.

[†] Windows and Windows XP are registered trademarks of Microsoft Corporation in the United States and other countries.

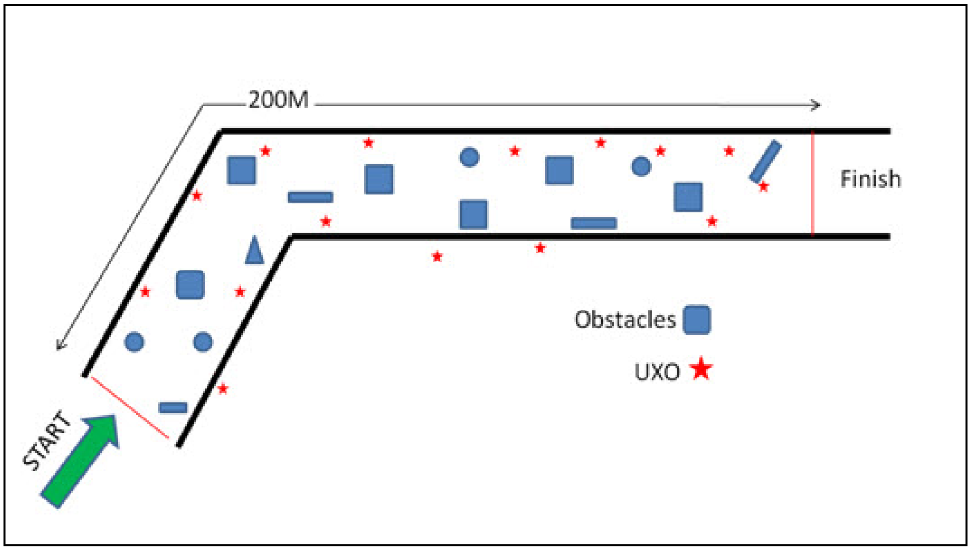

Figure 2. Robotic reconnaissance route.

2.2.4 The National Aeronautics and Space Administration-Task Load Index (NASA-TLX)

The NASA-TLX requires the user to rate the workload of a device on a number of different scales and to assign an importance weight to each scale. The scores on the workload scales (mental, physical, temporal, performance, effort, and frustration) can be combined in an overall workload score (Hart and Staveland, 1988).

2.2.5 Questionnaires

The questionnaires were designed to elicit Soldiers' opinions about their performance and experiences with each of the controller systems. The questionnaires asked the Soldiers to rate the devices on a 7-point semantic differential scale ranging from "extremely bad/difficult" to "extremely good/easy." Questionnaires were administered to each Soldier at the end of each iteration (with each type of controller) and at the end of the experiment. Questionnaires were also used to gather information concerning the Soldiers' demographic data, robotic experience, and physical characteristics that might affect their ability to operate the robot.

2.3 Procedures

2.3.1 Soldier Orientation

In the experiment Soldiers reported in groups of six for one day each, from 0800 to 1700 hours daily. Upon arrival, they received a roster number used to identify them throughout the evaluation. The Soldiers completed an informed consent form, medical status form, and a demographics questionnaire. They were given an oral operations order that explained the robotic mission that they would undertake during the experiment. The training and robotic courses were also explained, and any questions the Soldiers had concerning the experiment were answered.

2.3.2 Training

A representative from SSC Pacific trained the Soldiers on the use of the ISR robot. Soldiers practiced teleoperating the robot on the same routes used during the experiment to help mitigate learning effects. They were trained on each control condition just before executing the course with that condition. Soldiers were considered trained once they were able to complete the route without assistance. The average training time required was 20 min. Questionnaires concerning the amount of practice time given, the level of detail presented, and the adequacy of training aids were administered at the completion of training.

2.3.3 Reconnaissance Route Iterations

Soldiers completed three iterations of the robotic driving course, once using each level of autonomy (table 1). Each iteration with its associated level of autonomy consisted of three trials. The first was a training practice trial, the second was a record trial, and the third was a record trial with secondary tasks included. Soldiers were given an operations briefing that explained the robotic mission. During the briefing, it was explained that their primary task was to negotiate the route as quickly as possible without running into any of the obstacles and without leaving the roadway. Soldiers were also instructed to report any UXO they observed while traversing the route.

Table 1. Order of treatments and lanes.

Roster	Iteration 1	Iteration 2	Iteration 3
1, 7, 13, 19, 25	A	S	T
2, 8, 14, 20, 26	A	T	S
3, 9, 15, 21, 27	S	A	T
4, 10, 16, 22, 28	S	T	A
5, 11, 17, 23, 29	T	A	S
6, 12, 18, 24, 30	T	S	A

The Soldiers’ secondary tasks, conducted in the third trial, included reporting the following when requested by the data collector: current course time using a stop watch, the correct number codes using a matrix (table 2) when rows and columns were given, and the activities and location of a person of interest. The person of interest was located in the vicinity of the operator and performed various scripted activities during the course of the reconnaissance (table 3). Soldiers were required to report their responses to the secondary tasks via radio to the data collector. The secondary tasks served as an additional physical and cognitive load. Secondary task questions were asked at 20-second (s) intervals throughout the reconnaissance.

Table 2. Secondary task code matrix.

	A	**R**	**B**	**Q**	**C**	**P**	**D**	**O**	**E**	**N**	**F**	**M**	**G**	**L**	**H**	**K**	**I**	**J**
1	2	1	0	3	4	6	7	8	9	2	1	0	3	4	6	7	8	9
18	4	3	5	6	8	12	8	9	10	4	3	5	6	8	12	8	9	10
3	6	5	10	9	12	18	9	10	11	6	5	10	9	12	18	9	10	11
16	8	7	15	12	16	24	10	11	12	8	7	15	12	16	24	10	11	12
5	10	9	20	15	20	30	11	12	13	10	9	20	15	20	30	11	12	13
14	12	11	25	18	24	36	12	13	14	12	11	25	18	24	36	12	13	14
7	14	13	30	21	28	42	13	14	15	14	13	30	21	28	42	13	14	15
12	16	15	35	24	32	48	14	15	16	16	15	35	24	32	48	14	15	16
9	18	17	40	27	36	54	15	16	17	18	17	40	27	36	54	15	16	17
10	20	19	45	30	40	60	16	17	18	20	19	45	30	40	60	16	17	18
11	22	21	50	33	44	66	17	18	19	22	21	50	33	44	66	17	18	19
8	24	23	55	36	48	72	18	19	20	24	23	55	36	48	72	18	19	20
13	26	25	60	39	52	78	19	20	21	26	25	60	39	52	78	19	20	21
6	28	27	65	42	56	84	20	21	22	28	27	65	42	56	84	20	21	22
15	30	29	70	45	60	90	21	22	23	30	29	70	45	60	90	21	22	23
4	32	31	75	48	64	96	22	23	24	32	31	75	48	64	96	22	23	24
17	34	33	80	51	68	100	23	24	25	34	33	80	51	68	100	23	24	25
2	36	35	85	54	72	106	24	25	26	36	35	85	54	72	106	24	25	26

Table 3. Secondary task script.

Iteration #1 – Secondary Tasks – 20-s intervals	
1	Course Time
2	Matrix B-5
3	Person of Interest (behind operator with M-4)
4	Matrix P-6
5	Course Time
6	Person of Interest (left side behind operator with shovel)
7	Course Time
8	Matrix G-2
9	Person of Interest (right side behind operator with radio)
10	Course Time
11	Matrix E-10
12	Matrix H-9
13	Person of Interest (behind operator writing)
14	Course Time
15	Person of Interest (walking left to right)
Iteration #2 – Secondary Tasks – 20-s intervals	
1	Matrix J-2
2	Person of Interest (behind operator in prone position)
3	Course Time
4	Course Time
5	Matrix E-8
6	Person of Interest (behind operator with engineer tape)
7	Person of interest (left behind operator with M-4)
8	Course Time
9	Matrix M-13

Table 3. Secondary task script (continued).

Iteration #1 – Secondary Tasks – 20-s intervals	
10	Matrix L-11
11	Course Time
12	Person of interest (right behind operator talking on radio)
13	Matrix Q-15
14	Course Time
15	Person of Interest (standing with shovel)
Iteration #3 – Secondary Tasks – 20-s intervals	
1	Person of interest directly behind operator digging
2	Course Time
3	Matrix I-17
4	Course Time
5	Matrix F-10
6	Person of Interest (behind operator with radio)
7	Person of interest (left behind operator in prone position)
8	Course Time
9	Matrix C-9
10	Person of interest right behind operator with engineer tape
11	Course Time
12	Person of interest right behind operator with M-4
13	Matrix D-15
14	Course Time
15	Matrix O-8

A data collector following the robot recorded course completion time, number of driving errors, and number of times off course. A driving error was recorded when the robot ran into an obstacle or over UXO and an off course error was recorded if either track of the robot left the roadway. A data collector, co-located with the operator, recorded the number of secondary tasks performed correctly or incorrectly and recorded the number of UXO reported.

Upon completing each iteration, the Soldiers were given a questionnaire designed to assess their performance and experiences with each of the modes of operation. The participants also completed the NASA-TLX.

2.3.4 End of Experiment Questionnaire

After completing all three iterations, the Soldiers completed an end-of-experiment questionnaire that compared each of the control methods on a number of characteristics. They also completed questionnaires concerning the information requirements for teleoperating the robot.

3. Results

3.1 Demographics Results

The 27 participants were OCS candidates assigned to the OCS, Fort Benning, GA. The mean age of the Soldiers was 27 years (range 23–34), and the average time in service was 29 months (range 2–130). None of the Soldiers had any prior military experience in teleoperating a ground unmanned robot. Detailed responses to the demographics questionnaire are available in appendix A.

3.2 Training Results

Participants stated the training they received was thorough and fully prepared them to perform the tasks required to conduct the robotic reconnaissance course. Learning to operate the controls and drive the robot was rated as being very easy for all control conditions. Several Soldiers indicated that the hardest task to learn was maneuvering the robot around objects with the obstacle avoidance system turned on. Detailed responses to the training questionnaire are available in appendix B.

3.3 Robotic Reconnaissance Course Results

The summary statistics for course completion times, UXOs detected, and driving errors are shown in table 4.

Table 4. Means and (SDs), course time, UXOs detected and driving errors.

Without secondary tasks:

Measure	Teleoperation	Semi-autonomous	Autonomous
Time (min:sec)	2:43 (0:57)	3:13 (1:11)	2:37 (0:25)
UXOs detected	9.52 (3.19)	9.48 (3.48)	9.96 (3.20)
Errors	2.19 (2.29)	1.26 (1.38)	0

With secondary tasks:

Measure	Teleoperation	Semi-autonomous	Autonomous
Time (min:sec)	3:04 (1:04)	3:41 (1:13)	2:38 (0:22)
UXOs detected	9.07 (3.44)	10.15 (3.34)	9.22 (3.13)
Errors	2.44 (2.94)	1.04 (0.98)	0

The course completion times (figure 3) were analyzed using a repeated measures analysis of variance (ANOVA). The main effect for control modality [$F(2,52) = 10.5$, $p < .001$, $\eta^2_p = .287$] was statistically significant, as was the main effect for secondary tasks, $F(1,26) = 23.2$, $p < .001$, $\eta^2_p = .472$. The control x secondary task interaction was also statistically significant, $F(2,52) = 5.84$, $p = .005$, $\eta^2_p = .183$. Post-hoc paired comparisons were conducted using the Bonferroni correction for family-wise error. In both the teleoperation [$t(26) = 3.06$, $p < .05$, $d = .38$] and semi-autonomous control conditions [$t(26) = 4.45$, $p < .05$, $d = .55$], the participants completed the course significantly faster without the secondary tasks. In contrast, the secondary task had no significant effect on mean course times in the autonomous control condition, $t < 1$. The mean times for the semi-autonomous condition was slower than mean times for the teleoperation condition with [$t(26) = 5.56$, $p < .05$, $d = .69$] and without [$t(26) = 4.17$, $p < .05$, $d = .52$] the secondary tasks. Similarly, the mean times for the semi-autonomous condition were slower than means for the autonomous condition with [$t(26) = 9.18$, $p < .05$, $d = 1.14$] and without [$t(26) = 4.45$, $p < .05$, $d = .55$] the secondary tasks.

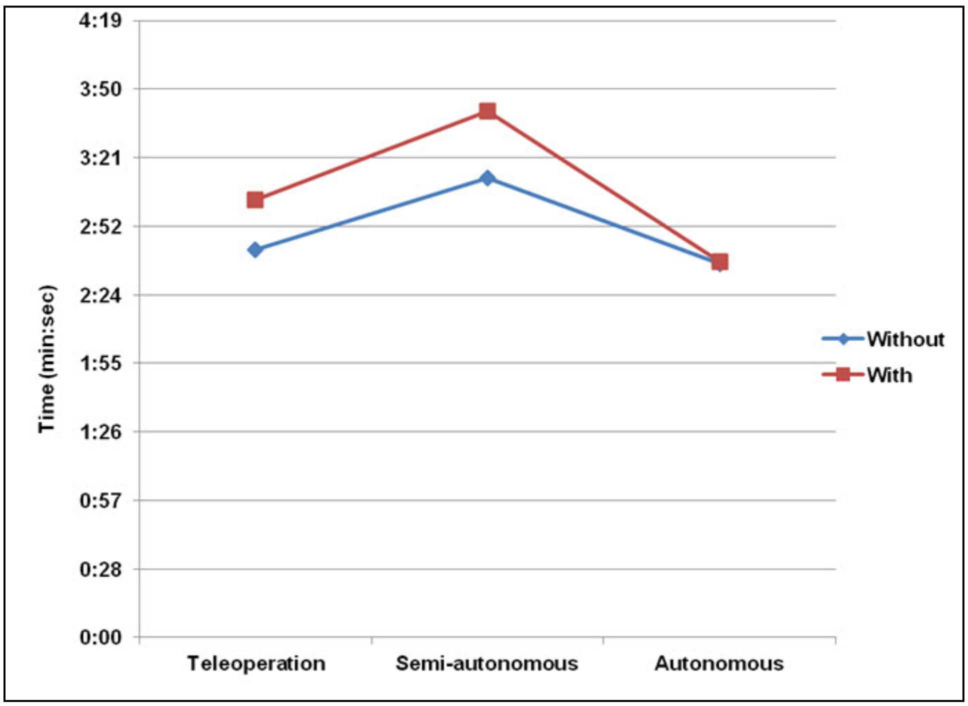

Figure 3. Course completion times (min:sec).

An analysis of the number of UXOs detected (figure 4) yielded no significant main effect for control condition, for secondary tasks, or for the control x secondary task interaction, all F's < 1. A ceiling effect was observed as Soldiers found most all of the UXOs.

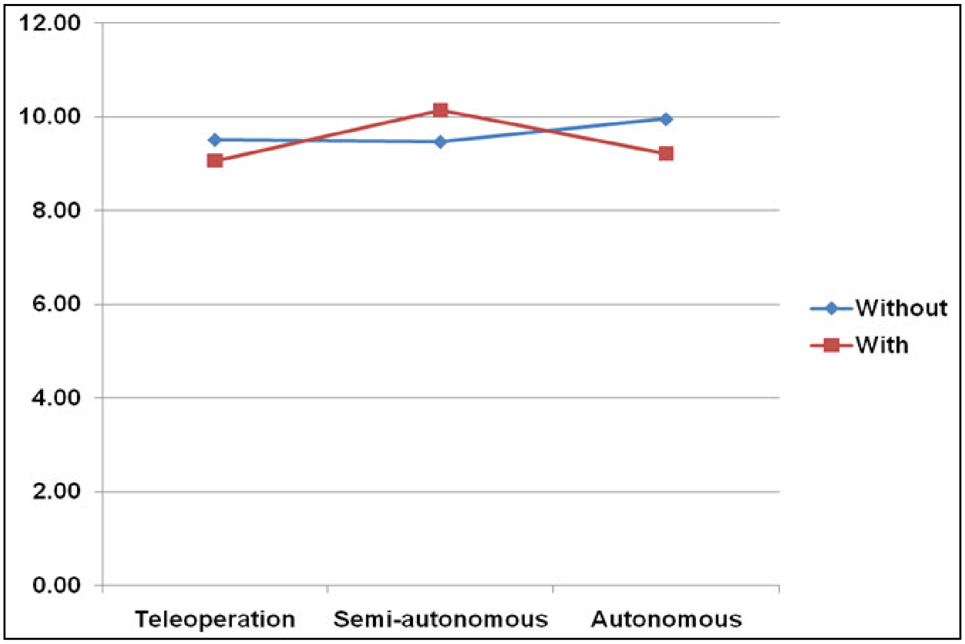

Figure 4. Mean number of UXOs detected.

There were no driving errors at all in the autonomous control condition (see figure 5). An analysis of driving errors in the teleoperation and semi-autonomous conditions indicated that there was a significant main effect for control condition [F(I, 26) = 5.57, p = .026, η^2_p = .176], with fewer driving errors in the semi-autonomous conditions. Neither the main effect for secondary tasks nor the interactions were statistically significant, both F's < 1.

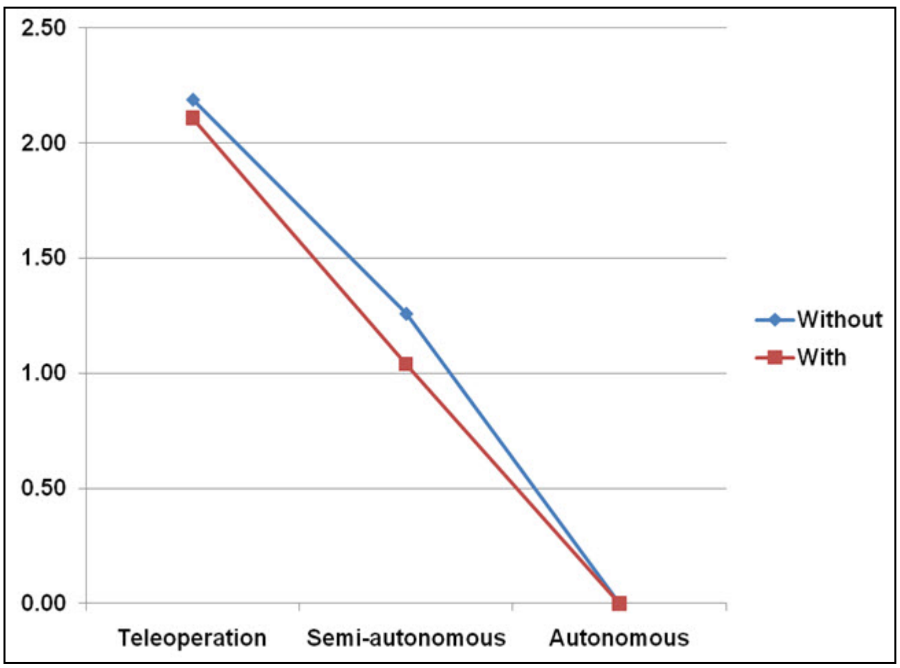

Figure 5. Mean number of driving errors.

Table 5 summarizes performance on the secondary tasks.

Table 5. Summary statistics, secondary task performance.

Secondary tasks	Teleoperation	Semi-autonomous	Autonomous
% correct	96% (8%)	98% (4%)	97% (9%)
% stop	73%	63%	5%

The participants responded correctly to almost all of the secondary task requests in all three control conditions; there were no significant differences among the conditions: $F(2,52) < 1$.

There was a statistically significant difference among the control conditions in the proportion of times the Soldier stopped operating the robot in order to respond to the secondary task request: $F(2,52) = 84.7$, $p < .001$, $\eta^2_p = .765$; figure 6. Follow-on paired-sample *t*-test comparisons were conducted using the Holm's sequential Bonferroni correction for family-wise error rate. As shown in table 6, there were significantly fewer stoppages in the autonomous condition than in the teleoperation or semi-autonomous conditions. The percentage of stoppages in the semi-autonomous condition and the teleoperation condition comparison approached significance and the effect size was moderate.

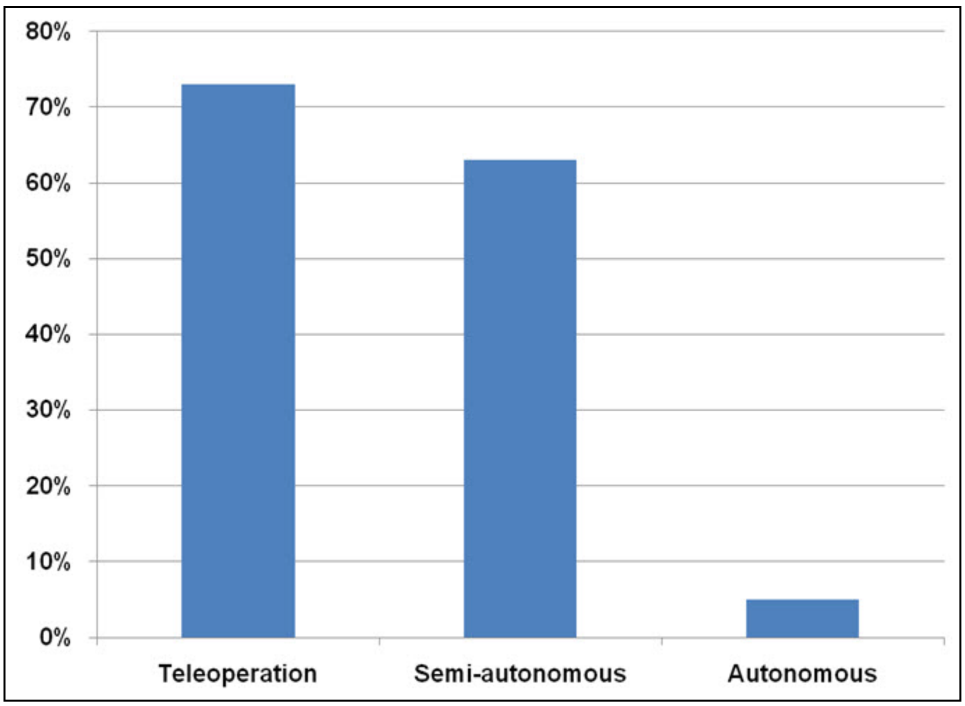

Figure 6. Percent of times Soldier stopped robotic operation in order to respond to secondary tasks.

Table 6. Follow-on comparisons, percentage stop.

Pair	*t*	*df*	obtained *p*	required *p*	Cohen's *d*
Tele vs. Semi	1.86	26	0.075	0.05	0.31
Tele vs. Auto	12.02	26	< .001	0.017	3.15
Semi vs. Auto	9.47	26	< .002	0.025	2.31

3.4 NASA-TLX Results

The NASA-TLX scale means and total workload means are shown in table 7 and figure 7.

Table 7. Means and (SDs), NASA-TLX

Scale	Teleoperation	Semi-autonomous	Autonomous
Mental	53.1 (22.2)	58.7 (21.6)	39.6 (20.6)
Physical	15.0 (12.6)	18.1 (16.3)	11.1 (9.7)
Temporal	53.9 (20.8)	52.2 (21.4)	42.8 (21.2)
Performance	36.5 (21.5)	42.8 (24.6)	33.7 (22.8)
Effort	51.5 (24.2)	52.2 (22.9)	39.3 (21.1)
Frustration	38.0 (22.4)	44.8 (28.6)	31.1 (19.7)
Total workload	48.5 (14.2)	52.8 (18.1)	39.0 (16.6)

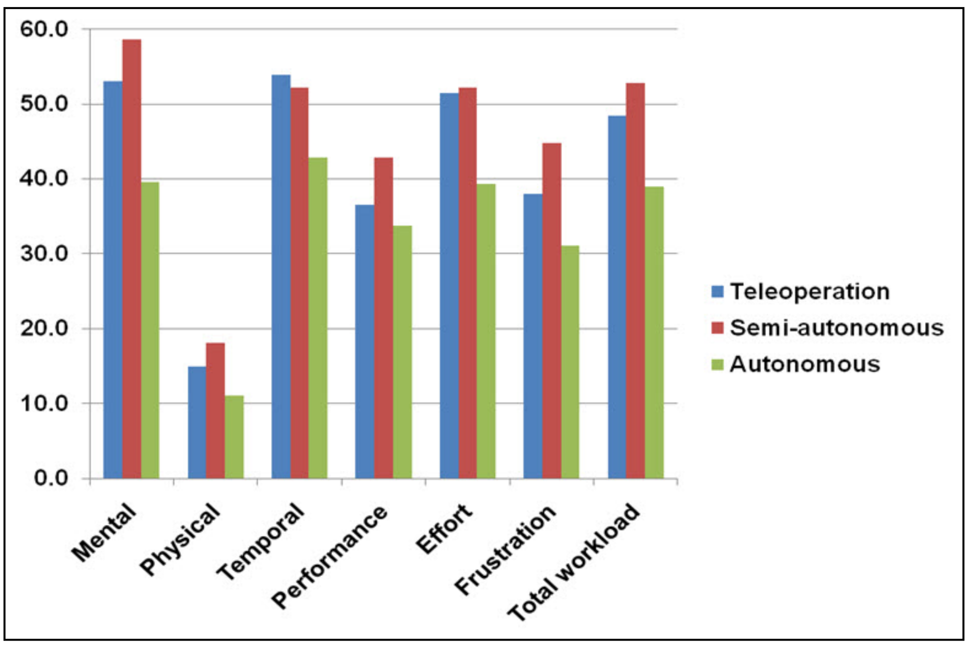

Figure 7. NASA-TLX scale means.

The repeated measures ANOVAs are summarized in table 8, and the follow-on paired comparisons are shown in table 9. On the Mental Scale, both teleoperation and semi-autonomous control received higher mean workload ratings than autonomous control. The semi-

autonomous control was rated higher than autonomous control in terms of Physical and Temporal demands. Autonomous control was rated as requiring less effort than teleoperation and semi-autonomous control. The semi-autonomous control was rated higher than autonomous control in terms of Frustration. Finally, autonomous control was rated as being lower in total workload than teleoperation and semi-autonomous control.

Table 8. Repeated measures ANOVAs, NASA-TLX.

Scale	**df**	***F***	***p***	η^2_p
Mental	2,52	11.30	< .001	0.302
Physical	2,52	4.94	0.011	0.160
Temporal	2,52	3.55	0.036	0.120
Performance	2,52	1.82	0.172	0.066
Effort	2,52	5.79	0.005	0.182
Frustration	2,52	3.62	0.034	0.122
Total workload	2,52	11.20	< .001	0.301

Table 9. Follow-on paired comparisons, NASA TLX.

Mental:

Pair	**t**	**df**	**obtained p**	**required p**	**Cohen's *d***
Tele vs. Semi	1.87	26	0.073	0.050	0.27
Tele vs. Auto	2.77	26	0.010*	0.025	0.66
Semi vs. Auto	4.41	26	< .001*	0.017	0.93

Physical:

Pair	**t**	**df**	**obtained p**	**required p**	**Cohen's *d***
Tele vs. Semi	1.50	26	0.147	0.050	0.15
Tele vs. Auto	1.96	26	0.061	0.025	0.19
Semi vs. Auto	2.72	26	0.012*	0.017	0.34

Temporal:

Pair	**t**	**df**	**obtained p**	**required p**	**Cohen's *d***
Tele vs. Semi	1.50	26	0.147	0.050	0.08
Tele vs. Auto	1.96	26	0.061	0.025	0.54
Semi vs. Auto	2.72	26	0.012*	0.017	0.46

Effort:

Pair	**t**	**df**	**obtained p**	**required p**	**Cohen's *d***
Tele vs. Semi	> 1	26	0.860	0.050	0.03
Tele vs. Auto	3.04	26	0.005*	0.017	0.59
Semi vs. Auto	2.80	26	0.009*	0.025	0.63

Frustration:

Pair	**t**	**df**	**obtained p**	**required p**	**Cohen's *d***
Tele vs. Semi	1.32	26	0.199	0.050	0.33
Tele vs. Auto	1.44	26	0.161	0.025	0.34
Semi vs. Auto	2.58	26	0.016*	0.017	0.67

Total workload:

Pair	**t**	**df**	**obtained p**	**required p**	**Cohen's *d***
Tele vs. Semi	1.53	26	0.137	0.050	0.21
Tele vs. Auto	3.04	26	0.005*	0.025	0.46
Semi vs. Auto	4.57	26	< .001*	0.017	0.67

** p < .05, 2-tailed*

3.5 Questionnaire Results

Upon completion of each iteration, Soldiers were asked to rate their ability to perform navigation/maneuver tasks on a 7-point semantic differential scale ranging from "extremely difficult" to "extremely easy." Figure 8 shows Soldier task ratings for each level of autonomy.

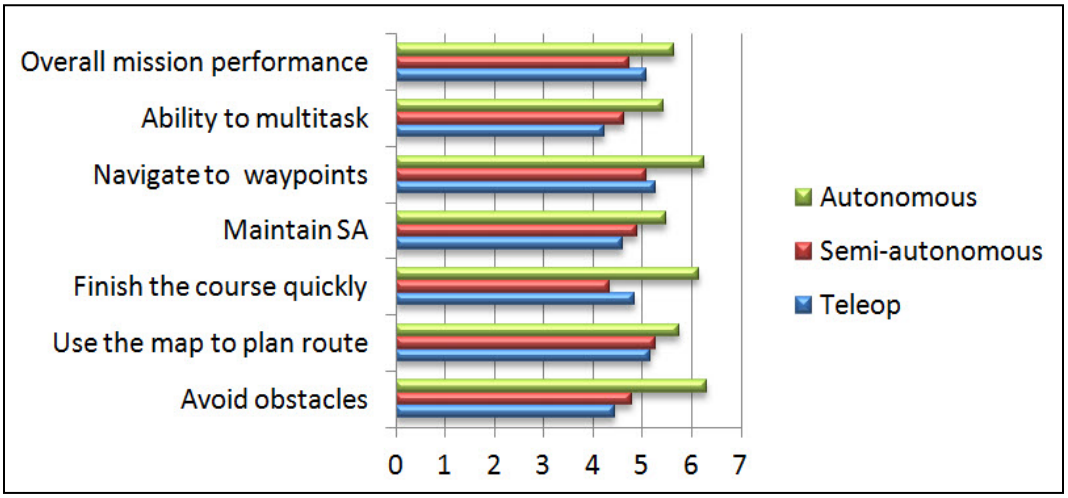

Figure 8. Soldier task ratings for each level of autonomy.

The Soldiers preferred full autonomy for all the navigation/maneuver tasks required to complete the reconnaissance course. Once the operator set the robot's desired destination and intermediary points, the robot traversed from point to point without further input from the operator. The hands-free nature of autonomous control enabled the Soldiers to focus more attention on the secondary tasks. The disadvantage of autonomous control identified by the Soldiers was the inability to thoroughly search the route for UXOs. In the autonomous mode, the robot continuously moves and automatically selects routes around obstacles. Several Soldiers stated that they would prefer to stop the robot when distracted by a secondary task so they would not miss something while they were looking away from the MOCU.

The semi-autonomous mode was preferred over the teleoperated mode for multitasking, maintaining SA, avoiding obstacles, and using the map to plan routes. Soldiers stated that when operating in the semi-autonomous mode, they could confidently move the robot faster without worrying about hitting obstacles and could perform secondary tasks easier than when fully teleoperating the robot. The disadvantage of the semi-autonomous mode identified by the Soldiers was the unpredictable nature of the guarded teleoperation behavior. When approaching an obstacle, the robot would automatically turn away from it to avoid contact. If the operator intended to go around an obstacle to the right or left side, the robot often turned away in the opposite direction causing the operator to take a different route than intended or having to back the robot up and re-approach it from a different angle. Several Soldiers stated that the unpredictable nature of the guarded teleoperation was frustrating and caused them to feel like they were competing for control of the robot.

In the teloperated mode, Soldiers stated they felt they had more control of the robot's speed and direction and they were able to perform a more thorough reconnaissance for UXOs. Several disadvantages of teleoperation were identified when compared to the other modes. Most Soldiers agreed that the teleoperation mode was more mentally and physically demanding and required more focus than the other modes, therefore making multi-tasking and secondary task performance more difficult. They also stated that teleoperation requires more skill with the controller to avoid hitting obstacles and UXOs.

Detailed responses to the post-iteration and end-of-experiment questionnaires are available in appendices C and D.

4. Discussion and Recommendations

Because the secondary tasks were fairly simple and the operators in many cases stopped the forward progress of the robot to perform the secondary tasks, the results exhibited a ceiling effect and it was impossible to compare the operators' situation awareness when using the three levels of autonomy to see if findings were similar to those of Chen and Joyner, 2006; Dixon et al., 2003; and Luck et al., 2006.

The guarded teleoperation capability of the robot created mixed results. Guarded teleoperation theoretically is useful in cluttered environments, as it can be used to prevent the operator from driving into objects easily detected by the robot, freeing them to concentrate on higher level decision making. However, Soldiers stated that the hardest thing to learn was how to maneuver the robot around objects when the obstacle avoidance system was being used. Although the obstacle avoidance system appeared to adversely impact course completion times, it did reduce the number of driving errors over those with teleoperation and it also reduced the percentage of times the operators had to stop driving in order to perform the secondary task over the teleoperation percentage. This capability needs to be refined so Soldiers can choose (if they desire) how to most efficiently maneuver around the detected objects rather than having to rely on what they feel is chance concerning which direction the robot will move after detection of an object.

Overall, the Soldiers preferred full autonomy and secondary tasks had little effect on the robotic driving tasks in this mode. However, Soldiers did not feel that they were as thorough when looking for UXOs because they had no control on the robot behavior and could not pan the area. Providing the capability to pan the camera to search for UXOs would allow more efficient and effective search performance. Performance using semi-autonomous control was mixed. Operators were able to perform secondary tasks without stopping the robot as much as they had to when teleoperating it and they had fewer driving errors than they did with teleoperation. However, course times were slower with the semi-autonomous mode, probably because the

guarded teleoperation capability made it difficult to efficiently maneuver around obstacles. Teleoperation was the least preferred mode; however, all primary and secondary tasks could be performed efficiently in this mode and Soldiers felt that this mode gave them more control to search efficiently for UXOs.

5. Conclusions

Operating the robot in the autonomous mode was the best condition for the tasks required by this experimental protocol. Secondary task requirements had little or no effect on primary task performance in this mode and the Soldiers preferred this mode of operation over the semi-autonomous and teleoperation modes.

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Appendix A. Demographics

This appendix appears in its original form, without editorial change.

SAMPLE SIZE = 27

Sex	**MOS**	**Rank**	**Duty Position**
Male – 20	09S – 18	E-4 – 14	OCS – 17
Female – 7	19K – 1	E-5 – 5	SGL – 1
	35F – 2	E-6 – 3	Tank Cdr – 1
	36B – 1	E-7 – 1	NR – 8
	88M – 1	NR – 4	
	92A – 1		
	NR – 3		

With which hand do you most often write? _23_ right _4_ left

With which hand do you most often fire a weapon? _25_ right _2_ left

Do you wear prescription lenses? _8_ No _19_ Yes

If Yes, which do you most often wear? _5_ Glasses _3_ Contacts

Do you wear glasses or contacts while firing a weapon? _6_ glasses _2_ contacts

Which is your dominant eye? _24_ Right _3_ Left

What is the highest level of education you have achieved?

_0_ GED _0_ High School _0_ Some college _0_ Two-year college degree

_21_ Bachelor's degree _6_ Master's degree

Where do you currently use a computer?

_18_ Home _14_ Work _1_ Library _0_ Do not use

Other: _7_ Barracks

	Mean	**SD**	**Range**
Your age:	27 yrs	2.8 yrs	23 - 34
Your height:	69 in	4.1 in	60 - 75
Your weight:	167 lbs	32.2 lbs	110 - 240
How long have you served in the military?	29 months	37.3	2 - 130

	No	Yes
Have you been a fire team leader?	25	2
Have you been a squad leader?	21	6
Have you been deployed overseas?	18	9
Have you been deployed in a combat area?	20	7

14. How often do you do/use the following?

	Number of Responses					
	Daily	**Weekly**	**Monthly**	**Once every few months**	**Rarely**	**Never**
Mouse	0	2	0	3	2	20
Joystick	5	14	4	1	2	1
Touch screen	0	3	0	1	0	23
Software with icons	0	0	0	0	2	25
Pull-down menu *****	0	0	0	0	3	24
Graphics/drawing features in software packages*****	3	8	1	4	3	8
Email	1	0	0	0	1	25
Operate a radio-controlled vehicle	14	11	2	0	0	0
Play first person shooter computer/video games	6	4	9	1	6	1
Use an X-box controller	7	4	6	4	5	1

***** *One 'no response'*

15. Using the scale below, please rate your skill level for each of the following activities?

	None	Beginner	Intermediate	Expert
Operating ground unmanned vehicles	23	3	0	0
Operating aerial unmanned vehicles	25	2	0	0
Target detection and identification	12	9	6	0
Playing commercial video games	3	11	5	8
Training with Army video simulations	7	15	5	0

16. How successful do you think you will be at robotic driving?

	Number of Responses
Very successful	4
Successful	11
Neutral	12
Unsuccessful	0
Very unsuccessful	0

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Appendix B. Training

This appendix appears in its original form, without editorial change.

SAMPLE SIZE = 27

1. Using the scale below, please rate the training that you received in the following areas:

1	2	3	4	5	6	7
Extremely difficult	Very difficult	Difficult	Neutral	Easy	Very easy	Extremely easy

TRAINING FEATURES	MEAN RESPONSE
Completeness of introductory training	6.22
Comprehension of the overall concept of the robot	6.33
Training on operating the robot (***Teleoperation***)	6.33
Training on operating the robot (***Semi-autonomous***)	6.07
Training on operating the robot (***Autonomous***)	6.19
Time provided to practice driving the robot on the route reconnaissance course	6.44
Explanation of how to complete the route reconnaissance course (independent of controller type)	6.41

2. What were the easiest and hardest training tasks to learn?

Comments	**No. of Responses**
Easiest	
Autonomous operation.	6
Use of controller.	1
Controlling the robot itself with the Xbox controller.	2
Xbox controller because of past experience and because it translates exactly.	1
Controlling robot in teleoperation.	4
Spotting items of interest.	1
Driving/operating the robot.	5
Ability to navigate the controller for the robot.	1
Driving the robot in semi-autonomous mode.	1
Moving in a straight line.	1
Good visuals.	1
The controls.	1
Reading the computer screen, layout, icons, etc.	1
Nice speed.	1
Controls speed well so you can maneuver around obstacles.	1
Avoiding obstacles.	1
Plotting the point on the map.	1
Creating the route.	1
Calling out IEDs.	1

Comments	No. of Responses
Hardest	
On semi-autonomous.	4
Semi-autonomous was probably harder to learn how to control, due to the fact it won't always go in the direction you tell it.	1
Semi-autonomous is hardest to learn because it's difficult to predict which way the robot will turn.	1
Competing with the semi-autonomous.	1
Seeing IEDs with the course resolution (of the camera) and in shadow driving in semi-autonomous mode.	1
Identifying the IEDs on the course while limited by robot resolution and jitter.	1
Adapting to the robot movements in semi-autonomous mode.	1
Teleoperation.	5
Using the OA software.	1
Controlling robot in close quarters.	1
Operating the robot while trying to answer the matrix.	1
How to drive robot and not hit objectives.	1
Performing secondary tasks while driving robot.	1
Ability to multi-task while controlling the robot and identifying IEDs.	1
Understanding the relation between the location of the camera on the robot and the image on the screen.	1
Being comfortable with the controller.	1
Adding the secondary action of "person of interest."	1
Having to multi-task, particularly when looking for the person of interest, was the most difficult task.	1
Programming the route, though it wasn't very difficult once explained.	1
It was difficult to predict which way it would turn to avoid obstacles.	1
Video malfunctions/glitches.	1
Sensitive joysticks.	1
Navigating with the joystick.	1
Spatial/depth perception.	1
Timing of reaction.	1
Lag on the screen.	1
Training comments	
Very professional and well done.	1
Enjoyable! I'm excited about new technology.	1
Very interesting.	1
Very straightforward.	1
Easy to follow along with.	1
Provided me a good understanding of how to control the robot and my mission.	1
Easy to understand the system and learn the controls.	1
Not as hard as I thought it would be; I believe anyone could operate the robot.	1

Comments	No. of Responses
My first time operating a robot; very satisfied and now interested in how this actually happens. I have heard robotics would be the future; this was definitely worth coming to train for.	1
Semi-autonomous was the best mix of positives from autonomous and teleoperation.	1
Teleoperation was easy to learn, but most difficult to perform.	
Possibly more specific instruction on how OA works and makes determinations would help to instruct the driver how to work with other than against the system.	1

Appendix C. Post Iteration

This appendix appears in its original form, without editorial change.

SAMPLE SIZE = 27

A (Teleoperation); B (Semi-autonomous); C (Autonomous)

1. Using the scale below, please rate your ability to perform each of the following **tasks** based on your experience with the autonomy level that you just used:

1	2	3	4	5	6	7
Extremely difficult	Very difficult	Difficult	Neutral	Easy	Very easy	Extremely easy

DRIVING TASKS	MEAN RESPONSE		
	A	B	C
a. Move the robot in the correct direction	5.30	4.41	6.43
b. Avoid obstacles	4.44	4.78	6.30
c. Turn quickly	4.26	3.96	6.25
d. Turn precisely	4.04	3.85	6.15
e. Anticipate whether turn radius of vehicle will allow a turn	4.15	4.19	6.00
f. Stop quickly	5.59	5.63	5.72
g. Get up to speed quickly	5.67	5.30	6.35
h. Adjust to the effects of system latency (lag)	5.11	4.48	5.73
i. Adjust to the feel of the control system	5.44	4.59	5.83
j. Use the map to plan route in advance	5.15	5.26	5.76
k. Drive at slowest speeds	5.52	5.04	5.53
l. Drive at medium speeds	5.46	5.23	5.53
m. Drive at fastest speeds	5.59	5.37	5.76
n. Finish the course quickly	4.85	4.33	6.16
o. Responsiveness of the robot to your commands	5.12	3.96	6.21
p. Drive a straight route	5.50	5.07	6.45
q. Maintain situation awareness	4.59	4.89	5.48
r. Navigate to the next waypoint or set of hash lines	5.27	5.08	6.25
s. Ability to multitask (operate/monitor robot and communicate on the radio)	4.22	4.63	5.44
t. Overall ability to perform this mission	5.07	4.74	5.63

2. Please comment on every task above that gave you difficulty and try to pinpoint the specific problem the system gave you.

Comments	**No. of Responses**
Teleoperation	
All tasks were fairly simple to accomplish.	1
Lease difficult of the three because it allowed for the quickest navigation of the course.	1

Comments	No. of Responses
I am not a gunner and did not have practice with the control function, but I assume it would be much easier with a little more practice. I also have pretty bad depth perception but accustomed to the robot quickly.	1
Multi-tasking.	2
Multi-tasking while controlling the robot was a challenge. I didn't feel comfortable moving the robot forward while performing other tasks.	1
Multi-task performing the many courses via hand controls, video screen, as well as communicating via radio was difficult.	1
Without the sensors, I tend to run into obstacles often.	1
If comms is direct, I feel that the comms should always be open and not require an over/out (pushing a button).	1
Avoiding obstacles, as the crosshair in the view is well off-centered.	1
I had some trouble judging turns around obstacles using the computer screen.	1
Much more difficult than with obstacle avoidance (OA). Unsure of robot in regards to obstacles. I thought I might have hit some after passing them on the camera view.	1
Not hitting the objects in the course. The size of the robot as I drove through the obstacles.	1
Navigating quickly around obstacles without touching them. This is likely the result of getting used to the joystick.	1
Being unfamiliar with the sizes of objects on the course made it difficult to maneuver and choose the best route around obstacles.	1
The robot ran into two obstacles. Some areas between obstacles seemed too tight of a space. This could have also been due to the fact that I underestimated the size of the robot.	1
Over steer and offset camera resulted in some obstacle collisions.	1
When turning the vehicle, I tended to over-correct.	1
There was some difficulty with seeing smaller objects due to picture quality and lag; picture quality greatly reduced depending on the sun.	1
Video lag was a problem.	1
Low screen resolution made it hard to spot IEDs, especially in the shadows.	2
It was difficult to spot IEDs which did not have a shape in contrast to the background.	1
Abruptly stopping the robot to do my tasks.	1
Takes more focus.	1
The matrix was the most difficult; mostly because I had to focus on it the most. The other objectives allowed me to keep my finger on the control while I performed a quick task. The matrix required me to literally pinpoint with my finger the answer to the question.	1
Still have to stop all movement to find items on the matrix. Very time consuming.	1

Comments	No. of Responses
Semi-autonomous	
No problems; easier than manual teleoperation mode.	1
The change in location when the screen resumed after a video lag was hard to adjust to.	2
Turning robot to correct direction (wasn't moving to direction on joystick).	1
Maneuvering the vehicle once it was 'stuck' because it kept trying to autocorrect at times I didn't desire it to.	1
Knowing whether it was you or the robot is taking control of the obstacle avoidance was difficult. Got stuck a few times.	2
I found semi much harder to control than teleoperation. When the robot corrected itself, I found the angles to be much more extreme than had I done it myself. I found myself more frustrated when it took over from me.	1
The robot did not respond twice when I attempted to make a sharp turn. I knew I was past an obstacle but the robot did not respond for a few seconds.	1
When the system used the OA software, it made the course slightly more difficult for a new user.	1
Compensating for the OA took time to maneuver better. When the robot avoided the obstacles, it wasn't easy to readjust smoothly.	1
In some tight situations, I had to fight the OA when my course correction called for in place rotation to either side.	1
When using the collision control function, it seemed to prevent my being able to maneuver the robot effectively.	1
Moving through close obstacles, the robot continued to correct as to not run into anything. This resulted in almost no movement through narrow corridors.	1
Avoiding obstacles, stemming from adjusting to the feel of the control system, making turns in particular.	1
Not knowing how the robot would avoid obstacles was hard; knowing it would veer right so many degrees would have helped.	1
In tight spots it looked as if I could make it through, but the controls wouldn't let me go.	2
Turning the robot quickly was difficult if the robot was near an obstacle and attempting to self-correct. Turning was, in general, slightly clumsy.	1
Getting the number from the matrix was very difficult for me.	1
The matrix caused me to completely stop what I was doing; was difficult while operating robot.	2
The matrix was somewhat difficult to read because of the letters and numbers being out of order.	1

Comments	No. of Responses
The task that requires me to report a number based on two coordinates slowed me down enough to simply allow the robot to sit still while I locate the two coordinates.	1
Feeling in control with direction, had difficulty remaining in a straight line.	1
Multi-tasking was very difficult because it was kind of hard to focus on driving while handling the radio and looking for the task.	1
Autonomous	
Very easy to use autonomous system. Gives you the ability to easily multi-task.	1
The movement from the robot is much faster and the ability to dodge obstacle was effortless.	1
Just a matter of getting familiarized with the screen and steps.	1
Setting points wasn't very precise because of the size of the map and the touch screen, but it was generally fine.	1
The sensor for dropping points was pretty sensitive, but other than that, very user friendly.	1
Where I was exactly on the map; the GPS wasn't responding well.	1
I forgot to switch to the map in order to begin plotting route.	1
The control system/map would be something that I would need more time to get used to.	1
Unable to control the robot's speed, but did not find this to be an issue.	1
Only difficulty was multi-tasking.	1
When trying to look up the number on the matrix, it was difficult to focus on the screen.	1
Identifying the person of interest required me to look away from the screen most severely. Scanning the matrix which is out of the order took longer than a sorted matrix.	1
The matrix not being in sequence reduced my ability to search for IEDs quickly.	1
Difficult identifying the person of interest while also attempting to identify IEDs along the route.	1
When I had to take my attention away from the screen, I didn't have the ability to stop the robot, leaving opportunity for me to miss spotting IEDs.	1
Screen resolution made positive IED identification difficult.	2
Sometimes I couldn't tell if it was an IED or other debris.	1
Identifying objects.	1
Harder to see IEDs in this mode.	1
Poor video quality.	1
Setting the course for the robot and difficulties seeing color images through the camera created the most difficulty.	1

Comments	**No. of Responses**
Frustrating because you would not speed up or slow down in situations where more visual information was needed to be gathered.	1
During the second run, I did not know how to connect/delete two assigned routes, which caused my final time to be longer than intended. I ended up deleting both routes and starting over with a new route.	1

3. Please check any of the following conditions that you may have experienced during this trial.

CONDITION	Number of Responses		
	A	B	C
Eyestrain	4	3	4
Tunnel vision	1	1	0
Headaches	0	0	0
Motion sickness	0	0	1
Nausea	0	0	0
Disorientation	0	0	1
Dizziness	0	0	0

Comments	**No. of Responses**
Teleoperation	
Seeing IEDs in the shaded portions of the lane's edges.	1
I was tense throughout the obstacle course.	1
Semi-autonomous	
Controlling the robot and performing tasks at the same time.	1
Autonomous	
Performing the secondary tasks and watching the screen concurrently.	1

4. Using the scale below, what is your **overall rating** of the controller condition that you used this iteration?

1	2	3	4	5	6	7
Extremely bad	Very Bad	Bad	Neutral	Good	Very Good	Extremely Good

MEAN RESPONSE		
A	B	C
5.52	4.93	5.81

Comments	No. of Responses
Teleoperation	
Overall the robot was easy to control, especially for someone completely new to the system.	1
I think the controls were easy to use and interpret.	
Much easier in terms of responsiveness.	1
It was a positive experience to have full control of the robot.	1
Full control of the robot allowed me to divert attention from driving to side and allowed me to turn the robot to assist in IED identification.	1
The robot was easy to drive and extremely responsive to commands in this mode.	1
Easy to drive because it did not jerk left or right because of small obstacles.	1
Other than lag, every other thing about the system was excellent.	1
Camera lag could create an issue; it seems to interrupt the overall mission of moving as fast as possible (no matter the stopwatch), just in general.	1
I think given more time and familiarity with the controls and the robot would eliminate a lot of the initial strain and frustration levels.	1
The only negatives were difficulties due to picture quality and lag.	1
Semi-autonomous	
Overall, I felt that this control iteration was successful.	1
Altogether, using the robot was easy to learn and simple, especially in more open areas.	1
The controls were very easy to use.	1
This control condition was much easier, being able to correct the robot, rather than correct myself, the robot and movement. The robot self corrected and allowed me to maneuver quickly through the course.	1
Less stressful than having full control of the robot, as there was no worry about hitting obstacles.	1
The automatic obstacle detection made it easy to drive fast with confidence.	2
Visibility of obstacles and items of interest was good.	1
The system indeed has a good mapping capability but the control really could use some fine tuning in terms of turning and making slow to medium speed maneuvers.	1
It was better than teleoperation, but I would prefer autonomous since it was difficult moving once the computer took over.	1
Worked great except through narrow passages.	1
In all situations, other than tight corridors, it was beyond easy to control. It took some adjustment to learn to work with and anticipate the OA course correction.	1
OA software was slightly difficult to adjust to.	1
Most difficulties were due to my own inexperience with the system.	1
I liked having the teleoperation control better because I consistently had control over the robot as opposed to intermittent control.	1

Comments	No. of Responses
I found the teleoperation easier just because I knew how the robot would move. Every time the robot veered because of an obstacle, I had to reorient myself to the surrounding obstacles.	1
I really struggled with maneuvering around obstacles, and felt I couldn’t drive while not having my eyes focused on the screen.	1
I stunk at this one!	1
High resolution camera, which I assume will be used anyway.	1
Autonomous	
This was the best! Being able to solely focus on obstacles, hazardous conditions made it less of an issue because full focus was on the condition of the route and objects throughout.	1
Overall, it went very well. With some practice, I could see myself getting used to seeing through the robot’s eyes.	1
Was good and allowed me to put a lot more focus into spotting IEDs better and faster than in the teleoperation.	1
Much easier than the teleoperation and leaves time for secondary tasks.	1
By far the easiest and least stressful.	1
Allowed less mental demand of steering the robot.	1
Allowed me to complete additional tasks with easy while knowing the primary mission would be accomplished swiftly.	1
Very simple, but with far less control once the robot started moving.	1
Although somewhat difficult, it was interesting to have other factors thrown into the mix like a real world situation. Autonomous mode made the situation a little more difficult because of the inability for the driver to stop the vehicle.	1
It was a lot easier to avoid hitting objects.	1
Give the operator the power to pause motion to accomplish simultaneous tasks while operating the robot.	1
I was better able to focus on surroundings, but unable to view terrain and conditions at my own pace.	1
Not having control or robot made me less observant.	1
The combination of control and observation in the semi-autonomous was better.	1

5. Using the scale below, please rate the degree to which the secondary task interfered with your ability to operate/monitor the robot.

1	2	3	4
Extreme interference	Moderate interference	Slight interference	No interference at all

	Number of Responses											
	Teleoperation				Semi-autonomous				Autonomous			
Scale above->	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Report numbers from matrix	6	12	8	1	6	11	9	1	4	6	14	3
Report time on course	0	6	15	6	0	1	18	8	0	0	13	14
Report on person of interest	4	9	12	2	3	7	13	4	1	8	11	7
Report on items of interest *****	0	8	6	10	1	3	10	10	0	6	5	13

***** *3 no responses*

Comments	**No. of Responses**
Teleoperation	
Overall exercise was easy to navigate and adjust to.	1
It was easy to operate the radio because the controller only needed my left hand to operate it; but looking around, especially at the POI, was difficult because the robot was still moving and it inhibited my ability to spot IEDs because I was focused on other areas.	1
Being able to pause at will using the controller for brief intervals eliminated the pressure of multi-tasking and made the course easy.	1
Camera jerk was predictable and controllable.	1
Comms; having to establish communication by pushing the button on the mic was very distracting, as well as turning to see the person of interest.	1
The secondary tasks were not difficult or distracting except when they occurred during a set of obstacles.	1
Matrix was the toughest secondary task.	2
Having to search for the letter and number on the matrix takes at least a few seconds.	2
A larger font size and familiarity with the matrix would most likely be much easier.	1
Had to stop what I was doing to perform secondary task.	1
When maneuvering around/avoiding obstacles, I had to leave off of driving to complete the secondary tasks.	1
Turning from the screen completely caused a delay in reorienting direction and screen location.	2
Whenever a task called for me to take my eyes off of the screen, it caused an extreme interference because I had to readjust my eyes to the screen and readjust my mental focus. The matrix was the most extreme interference because I had to locate the plots and come up with a coordinate as opposed to just observing something and reporting that back.	1

Comments	No. of Responses
Hard to turn around to locate and describe person of interest. Indeed, it took away my ability and concentration for the task at hand to operate the robot and identify IEDs.	1
Semi-autonomous	
Not as much as the last time, since I did not have to worry about running into objects.	2
Desirable interference with robot correcting itself in front of objects.	1
The secondary task interference made the exercise somewhat more difficult paired with the OA software.	1
I assumed the letters from the matrix would be in alphabetical order. That messed me up.	1
The matrix is evil.	1
The numbers were easily the hardest task.	1
Again, plotting the numbers from the matrix takes more time and effort, as opposed to just reporting objects, persons of interest, or a time that is easily observable.	1
The numbers slowed me down by having me to switch from tunnel vision to side-to-side, plus up and down eye movements. Time and person of interest was easier because of the easy recognition.	1
If and when to report IEDs in relation to waypoints. I saw IEDs but due to proximity to waypoints I could not tell if they fell under the former or latter points.	1
Depending on whether I was maneuvering in the open or between obstacles, my ability to perform the secondary tasks was either easy or slightly difficult.	1
Considering the system setup during this iteration, it was necessary to stop the robot when reporting on the radio.	1
Autonomous	
Quite easy.	1
Makes it much easier to multi-task. Reporting over the radio is simplified on account of my having both hands free.	1
Overall great exercise.	1
Much easier to handle secondary tasks.	1
It was easier than any other mode because I can just react to secondary tasks instead of anticipating it.	1
The robot navigating on it’s on was more efficient.	1
Allowed me to look further up the road and spot IEDs faster while also allowing me some time to look around to complete the secondary tasks.	1
Somewhat frustrating, but good practice for real world scenarios.	1
Plotting numbers from the matrix remain the most difficult because it takes the most time and attention away from the screen.	1
My eyes were taken off the screen for at least 3-4 seconds when reporting from the matrix. It seemed impossible for me not to miss a possible IED.	1
Reporting the numbers was still time consuming, but overall much better than having the controls to worry about.	1

Comments	No. of Responses
Only problem is that robot will choose its own direction to travel. If you miss an item of interest, you cannot turn around to double check.	1
I felt like I was more focused on watching the path of the robot and less on the secondary tasks.	1
Secondary tasks were only difficult due to small matrix size and feeling pressured to look quickly while the robot continued to move forward, so no IEDs would be missed.	1
The longer I had to search for numbers or the person of interest the more I felt I was missing potential IEDs on the course. Quick tasks like checking the time were insignificant breaks. As the robot drove itself I could afford to only look for IEDs rather than focus on driving.	1
The camera was not focusing as quickly on the screen as needed due to light from sun.	1
Harder to see items of interest on the course.	1

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Appendix D. End of Experiment

This appendix appears in its original form, without editorial change.

SAMPLE SIZE = 27

1. Please indicate your 1st, 2nd and 3rd choice of the level of autonomy to use for completing the following tasks by placing a 1, 2, or 3 in the appropriate column.

1 = Best; 2 = Second best; 3 = Worst

Tasks	**Number of Responses***								
	Teleoperation			**Semi-Autonomous**			**Autonomous**		
Scale above ->	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Route reconnaissance	12	7	7	5	13	9	10	6	10
Moving around obstacles	14	6	6	4	13	10	9	7	10
Assessing the route for navigability	18	1	7	3	17	7	6	8	12
Completing recon course quickly	11	5	10	4	11	12	12	10	4
Performing radio tasks while using controller	5	11	10	2	11	14	20	4	1
Overall route reconnaissance	13	4	9	5	10	12	9	12	5

**sample size varied due to a 'no response' for some tasks*

Comments	**No. of Responses**
Teleoperation	
Teleoperation is simple and efficient.	1
It is easier to do individual task in teleoperation.	1
Secondary tasks made easier.	1
Semi-autonomous	
Semi-autonomous seemed to be the right amount of help from robot to confidently navigate course.	1
Semi-autonomous gave robot conflicting instruction from user and sensors on robot.	1
Sensor really interfered with maneuverability.	1
Autonomous	
Conducting all tasks simultaneously is easier in the autonomous mode.	1
Least distracting, but made more specific recon difficult.	1
General comments	
Teleoperation and semi-autonomous are virtually identical in most respects to radio tasks and recon. They only differ in level of control.	1

2. Using the scale below, what is your rating of the characteristics of the control and display system that you used during this experiment?

1	2	3	4	5	6	7
Extremely bad	Very Bad	Bad	Neutral	Good	Very Good	Extremely Good

CHARACTERISTICS	MEAN RESPONSE
Display size for driving	5.41
Display size for seeing IEDs	4.41
Size of the symbols and icons on the screen	5.56
Display layout	5.70
Map fidelity	5.26
Appearance of the graphic user interface (GUI)	5.63
Size of the buttons on the controller	6.33
Overall controller size for use in the field	6.30
Controller configuration for use in the field	6.15

Comments	**No. of Responses**
Controller is perfect size for operations in the field.	1
Very easy to use.	3
Have had experience with video game system controllers.	1
It was helpful to have a controller that is familiar to people.	1
Controller should be smaller; seems too bulky for use in the field.	1
Symbols on map could be smaller.	1
The IEDs were difficult to identify. Perhaps it was due to the graininess of the video; sometimes they were indistinguishable.	1
Resolution on the display made it hard to spot IEDs.	1
Resolution on the display made it hard to spot IEDs, especially in autonomous mode.	1
I would recommend the direction cross similar to the Nintendo 8-bit system controller instead of the mini joystick.	1
The camera resolution was very poor and greatly affected by ambient lighting.	1

3. What are the ADVANTAGES of operating the robot in the TELOPERATION mode?

Comments	**No. of Responses**
Overall, I thought this was the best mode.	1
Self-control; move slow or fast, not just one speed.	1
Control and predictability of movement and speed.	1
Complete user control increases the speed at which the course can be completed.	1
Easier to maneuver.	1
It can maneuver quickly around obstacles.	1

Comments	No. of Responses
Ease of movement in turns.	1
Driving is easier.	1
Fast.	2
You can assess situations/obstacles that a computer may not pick up on.	1
Full control over recon.	1
Full control of robot.	9
No need to worry or wonder which direction it will turn.	1
Easier to go in reverse to check on IED.	1
Constant choice of view.	1
You can easily investigate objects.	1
You are able to explore the course more and search for objects.	1
By the time is started this mode, I was familiar with the fell of the controller, icons, etc.	1
Hands free available for secondary tasks.	1

4. What are the DISADVANTAGES of operating the robot in the TELOPERATION mode?

Comments	No. of Responses
User error is much more likely.	1
Being reliant only on one's steering ability.	1
The amount of brain power going into driving.	1
Difficult to multi-task.	3
You must stop to multi-task in proximity to obstacles.	1
More mistakes, less time to be able to concentrate on all objectives of the mission.	1
I may let my guard down and let my mind wander.	1
GPS system was not working well. This skewed the map fidelity downward.	1
Slower.	2
Less confidence.	1
I may not feel that I am in complete control.	1
Hitting obstacles.	6
In an obstacle laden environment, teleoperation mode makes it easier to hit obstacles.	1
You will hit obstacles if you don't pay attention at all times.	1
No way to avoid obstacles if new to operating system.	1
Does not provide corrective obstacle/route function. I ran into an obstacle twice.	1
Not being able to maneuver around all the obstacles.	2
Navigating around single obstacles takes longer.	1
Very easy to get tunnel vision and hit objects.	1
Collisions more likely.	1
Takes a lot of focus.	1

Comments	No. of Responses
Harder to complete secondary tasks.	2
Wasn't paying attention to IEDs as much, and paying attention to the route.	1
Must be more skilled with the handheld controller.	1

5. What are the ADVANTAGES of operating the robot in the SEMI-AUTONOMOUS mode?

None.	1
Maintains most fine control advantages of teleoperation that autonomous lacks.	1
Robot self-corrects at obstacles.	3
Total control and freedom to look around if needed for short periods.	1
It will not allow you to collide with anything.	2
Confidence in not hitting obstacles.	4
Makes clearing/maneuvering around obstacles easier.	8
Moving around single obstacles is more fluid.	1
Speed.	1
You can move faster without worrying about hitting something.	1
Can just hold control forward while conducting a secondary task.	1
Easier to perform secondary tasks.	1
You can scan more easily without getting tunnel vision.	1
You can multi-task.	1
Easier to multi-task without having to worry about hitting something.	1
More time spent looking for IEDs, not driving.	1
If given practice enough to become accustomed to the driving technique required, could be most efficient.	1

6. What are the DISADVANTAGES of operating the robot in the SEMI-AUTONOMOUS mode?

Comments	No. of Responses
Complacency; thinking or guessing the robot will stop sometimes when it may not.	1
Not having full control of the robot.	2
Harder to control.	1
It was difficult to determine when I was controlling the robot and when it was controlling itself.	1
Have to navigate around objects at times.	1
Robot seemed to turn away from obstacle when I didn't want it to.	1
Unpredictability in where the robot heads around obstacles.	1
Have to fight the controls when the robot is wedged in between obstacles. Robot sometimes has a preferred route when it finds a clear route ahead.	1
You are unable to push or bump obstacles.	1
When avoiding obstacles, it sometimes makes it harder for you to regain	2

Comments	**No. of Responses**
full control of the robot to place it back on track.	
Although it deviates from running into obstacles, it slowed my mission time because I had to move the robot back on route.	1
Robot tends to lag.	1
Required variable levels of focus depending on number of obstacles.	1
Some spaces where the robot can fit are a no-go because the robot thinks it can't fit.	1
Difficult to navigate tight spaces.	4
Lack of freedom of movement in narrow corridors.	1
Less time to concentrate on objectives (i.e., quick finish, IEDs, etc.).	1
You have to stop when your attention is drawn to something time consuming to investigate.	1
Difficult to adjust to if new to the system.	1
Jerky at times.	1
More difficult to maneuver.	1
Angles shift too far on their own.	1
Must accommodate speed with the programs.	1
Hard to tell whose turn it is.	1
Takes the most practice to become accustomed to handling.	1
Using the joystick to practically wrestle with the sensor causes frustration.	1
Detracts the most from situational awareness.	1

7. What are the ADVANTAGES of operating the robot in the AUTONOMOUS mode?

Comments	**No. of Responses**
You don't have to monitor the robot the whole time.	1
Easy controls.	1
Having control.	1
Full control over how the robot moves.	1
Easy to navigate objects because it does it for you.	1
The robot completes the path without your help.	1
No focus need be spent on operation of the robot. All side tasks can be accomplished while the robot remains in motion.	1
The robot handles itself and avoids obstacles very well, allowing the controller to have the most situational awareness.	2
Fully controlled; ability to focus on one part of the mission vs. multi-tasking while controlling the robot and telling it what to do.	1
Took the stress out of dealing with the route and maneuver the robot.	1
Ability to multi-task very easily.	8
Takes the issue of operating the system with secondary tasks out of the equation.	1
Allows better completion of secondary tasks.	4
I did not have to operate the controller and was able to focus solely on my secondary tasks.	1

Comments	No. of Responses
Conducting secondary tasks seems less distracting.	1
Spend more time on surveillance.	1
Hands-free operation.	1
Speed.	2
Easy map layout.	1
Less chance of hitting an object.	1
Easier to spot IEDs.	2
A better look at suspicious objects.	1
Fewer demands.	1
Less focus is required.	1

8. What are the DISADVANTAGES of operating the robot in the AUTONOMOUS mode?

Comments	No. of Responses
Using the computer route functions can be a disadvantage if not properly trained on deleting routes/points.	1
None here at training, but if the robot makes a mistake anything could happen. Subjective question considering the robot made no mistakes.	1
Very easy to overlook something when you get distracted, since the robot doesn't stop moving.	1
Can't stop to look around as quickly.	1
You stop paying close attention to the map, which could be a potential issue.	1
Might not go the way you need, if a problem occurs rapidly.	1
Lack of control.	4
No total control over the robot which makes searching for individual objects more difficult.	1
No ability to slow down or scan the area at will to better see the ground.	1
No fine controls available to assist in identifying IEDs on the course.	1
No control over route selection.	1
You do not have control over the robot to scan for IEDs.	1
You could miss an IED because you cannot pause to get a decent look at something.	2
Robot continuously moves which makes identifying IEDs and persons of interest more difficult.	1
Can't double back without taking control.	1
Robot moves past obstacles without you seeing them.	1
Not having help and engaging all the obstacles by yourself.	1
Certain situations in a field environment may require humans making decisions vs. a computer system.	1
One is reliant on all the mechanisms of the robot to function properly.	1
Tasks are more difficult to report.	1
I may have a harder time reacting to secondary tasks.	1

Comments	No. of Responses
Poor ability to perform full recon.	1
Not the fastest.	1

9. What needs to be added to the controller to give you more knowledge of the area around the robot?

Overall great concept; great tool.	1
Good stuff; it seemed to suffice.	1
A mic and radio in case in the semi-autonomous or teleoperation mode.	1
Wider view camera.	1
Different lens so less fishbowl effect for better depth perception.	1
Lightening of shaded imagery and higher resolution, with fewer video freezes, which are disorienting.	1
Zoom feature on camera.	1
More cameras (views).	1
Better resolution for the camera.	2
Camera angle/direction control.	1
Ability to control the camera to move in every direction.	3
Ability to look up and down.	1
Swivel the camera to see the area around you.	1
Ability to move camera by itself instead of the whole robot.	1
Less lag time on camera.	1
Ability to control the camera to see if you are going to hit something.	1
Ability to maneuver the camera in addition to the robot itself would be helpful.	1
Something similar to side mirrors.	1
More sensitive robot directional controls.	1
Move the crosshairs to be centered as one drives, not centered on the camera.	1
Maybe before initial acceleration, have lines pop up temporarily to show the robot's borders.	1
Maybe a rumble pack or vibration function when approaching an obstacles.	1
An indication of what the robot senses during semi-autonomous mode so the user can work with the robot to resolve collisions.	1
More peripheral vision should be available to the controller to expand his/her field of vision. The quality of the video would also be helpful. A crisper, more precise video.	1

10. Overall comments:

Comments	No. of Responses
Very professional training and instruction.	1
Good work!	1
Good piece of equipment.	1

Comments	No. of Responses
Enjoyable!	1
It was an experience that every soldier should have and get a general idea of how the system works.	1
Great robot. Works well and does what it is intended to do.	1
Robot is easy to use for a new operator.	1
Good course.	2
Good overall experiment with a good user interface and joystick.	1
Easier to spot IEDs with some measure of control. Likely due to predictable and controllable camera jitter. Similar to driving a car, it is easier to predict shifts and motion when in control than when riding as a passenger.	1
Suggest upgrading to a higher definition camera to see picture a little clearer.	1
The robot would benefit from a parallax correctable camera, however, in terms of it making it easier for the operator to account for the size of the device.	1

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List of Symbols, Abbreviations, and Acronyms

ANOVA	analysis of variance
ARL	U.S. Army Research Laboratory
COTS	commercial off-the-shelf
EMCCD	Electron Multiplying Charge Coupled Device
FLIR	forward-looking infrared radar
GPS	global positioning system
HRED	Human Research and Engineering Directorate
IED	improvised explosive device
ISR	intelligence, surveillance, and reconnaissance
MOCU	Multi-Robot Operator Control Unit
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
OA	obstacle avoidance
OCS	Officer Candidate School
s or sec	second
SA	situation awareness
SSC Pacific	Space and Naval Warfare Systems Center, San Diego Pacific
STORM	Small Tactical Optical Rifle Mounted
UXO	unexploded ordinance

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